
Chapter 8

Synthesis: a palaeogeographic reconstruction of the Mount Windsor Formation and Trooper Creek Formation during the Cambro-Ordovician

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8.1 Introduction

A detailed analysis of the Mount Windsor Formation and Trooper Creek Formation, in the area between Coronation homestead and Trooper Creek prospect (approximately 15 km strike length), has helped clarify the facies architecture of the Cambro-Ordovician Seventy Mile Range Group. Significant advances have been made in understanding the character and geometry of the submarine silicic to intermediate volcanic succession, and assessing genetic links between volcanic, alteration and mineralisation processes. The research addresses a number of specific problems which are relevant to understanding other ancient submarine volcanic successions. These include:

- (1) the lithofacies and volcanic history of andesitic, shallow-marine strombolian volcanoes (Chapter 4);
- (2) constraints on the lithofacies associations and volcanic (and sub-volcanic) history of submarine silicic lava- and intrusion-dominated volcanic centres (Chapter 5);
- (3) assessment of the influence of sub-volcanic intrusions and domes on the genesis, localisation and evolution of syn-genetic submarine hydrothermal systems (Chapters 5-7);
- (4) volcanic influences on the formation of iron oxide±silica units ("ironstones") and relationships between ironstones and massive sulfide mineralisation (Chapter 6);
- (5) assessment of the diagnostic/critical evidence for sub-seafloor replacement style massive sulfide mineralisation, and the role of lithofacies in determining the character of the resulting deposit (Chapter 7).

The principal findings of this research are an understanding of the Cu-Au-rich Highway-Reward massive sulfide deposit and clarification of lithofacies and stratigraphy of the Seventy Mile Range Group.

8.2 Palaeogeographic reconstruction

In this section, the various elements of the preserved facies architecture are combined to reconstruct the Cambro-Ordovician palaeogeographic setting and volcanic history during accumulation of the Mount Windsor Formation and Trooper Creek Formation in the central part of the Seventy Mile Range Group.

8.2.1 Puddler Creek Formation

The oldest part of the Seventy Mile Range Group is the Puddler Creek Formation. The formation comprises a thick (?9 km, Henderson, 1986) sedimentary succession and minor basaltic to andesitic volcanics. The siltstone and sandstone units are dominantly continentally-derived but contain minor volcanic detritus. The lithofacies associations suggest that the depositional setting for the Puddler Creek Formation was submarine (below storm wave base).

8.2.2 Mount Windsor Formation

The Mount Windsor Formation marks the onset of voluminous silicic volcanism in the Seventy Mile Range Group. The formation comprises a thick sequence of rhyolitic volcanic rocks with minor dacite and andesite. Associations of coherent facies and autoclastic breccia facies, 100-500 m thick, form lavas and intrusions. The feeder dykes for the extrusive units have not been identified. However, mapping of the unit boundaries suggests that many lavas probably extended less than a few kilometres from their vents. The paucity of intervening volcano-sedimentary units implies that the lavas were erupted rapidly from adjacent vents or from fissures, and probably constructed significant topography that strongly influenced sedimentation patterns. Henderson (1986) argued that thickening of the Mount Windsor Formation between Highway-Reward and Sunrise Spur indicated an eastern source for the formation. As the lavas and intrusions are proximal to vent, it is more likely that the rhyolitic and dacitic units were erupted from separate intrabasinal vents distributed along the length of the basin, and that volcanic centres in the east were more productive.

The lavas and intrusions yield little unambiguous information about the depositional setting. Hyaloclastite associated with the lavas provides evidence for emplacement in a subaqueous environment. West of the study area at Mount Windsor, the Mount Windsor Formation includes resedimented volcanoclastic units interpreted to have been deposited from sediment gravity flows in a submarine environment (Berry et al., 1992). At

Thalanga (Fig. 1.1), VHMS-style mineralisation is partly hosted by volcanoclastic rocks of the Mount Windsor Formation, suggesting that this part of the Mount Windsor Formation accumulated below storm wave base in a submarine setting (Hill, 1996).

8.2.3 Trooper Creek Formation

Water depth and depositional setting

The Trooper Creek Formation comprises coherent lithofacies and compositionally and texturally diverse volcanoclastic lithofacies which are intercalated with lavas, intrusions and non-volcanic sedimentary facies (Chapter 3). The sedimentary facies contain marine fossils. Voluminous hyaloclastite, syn-sedimentary sills and local pillow lavas are also consistent with a submarine setting (cf. Berry et al., 1992). In the study area, the widespread occurrence of turbidites and thick intervals of siltstone suggests that most of the succession accumulated below storm wave base. Depth of storm wave base varies in modern environments from 10 to 200 m (Johnson and Baldwin, 1996). At Highway East, the presence of proximal bomb-rich andesitic breccia facies implies that the depositional environment was, at least locally, less than about 500 m deep (Chapter 5). Combined, the lithofacies associations, fossils and regional context imply that depositional setting of the Trooper Creek Formation was submarine, below storm wave base, and possibly not in extremely deep water. The exception is at Trooper Creek prospect where the depositional setting for the upper part of the Trooper Creek Formation was shallow marine (Chapter 4). Stromatolites, traction current deposits indicative of wave activity, and evaporitic minerals collectively suggest that this part of the succession was deposited above storm wave base and may have been temporarily emergent. Further work is required to determine if the facies associations at Trooper Creek prospect record a local shoaling depositional environment or regional shallowing of the basin east of Trooper Creek.

Lithofacies and volcanic history

The large volume rhyolitic effusive eruptions of the Mount Windsor Formation were followed by a phase of rhyolitic to basaltic effusive and explosive volcanism, and sedimentation. This phase in the history of the Seventy Mile Range Group is recorded by the Trooper Creek Formation. The Trooper Creek Formation is subdivided into two members, the Kitchenrock Hill Member and the overlying Highway Member. The stratigraphic subdivision is based on lithological variations which reflect different provenance characteristics.

Kitchenrock Hill Member

The volcanoclastic facies in the Kitchenrock Hill Member contain abundant rounded rhyolitic and dacitic clasts with geochemical and petrographic characteristics that suggest they were sourced from the Mount Windsor Formation (Chapter 3). Rounding occurred in a high-energy environment (above storm wave base) prior to redeposition, suggesting that the source areas were subaerial to shallow marine and that the volcanoclastic mass flows transgressed a shallow-water environment (Fig. 8.1). Alternatively, the clasts may have been collected somewhere along the flow path from already deposited material in a below-storm-wave-base environment. The sources of the rounded clasts are located outside the study area.

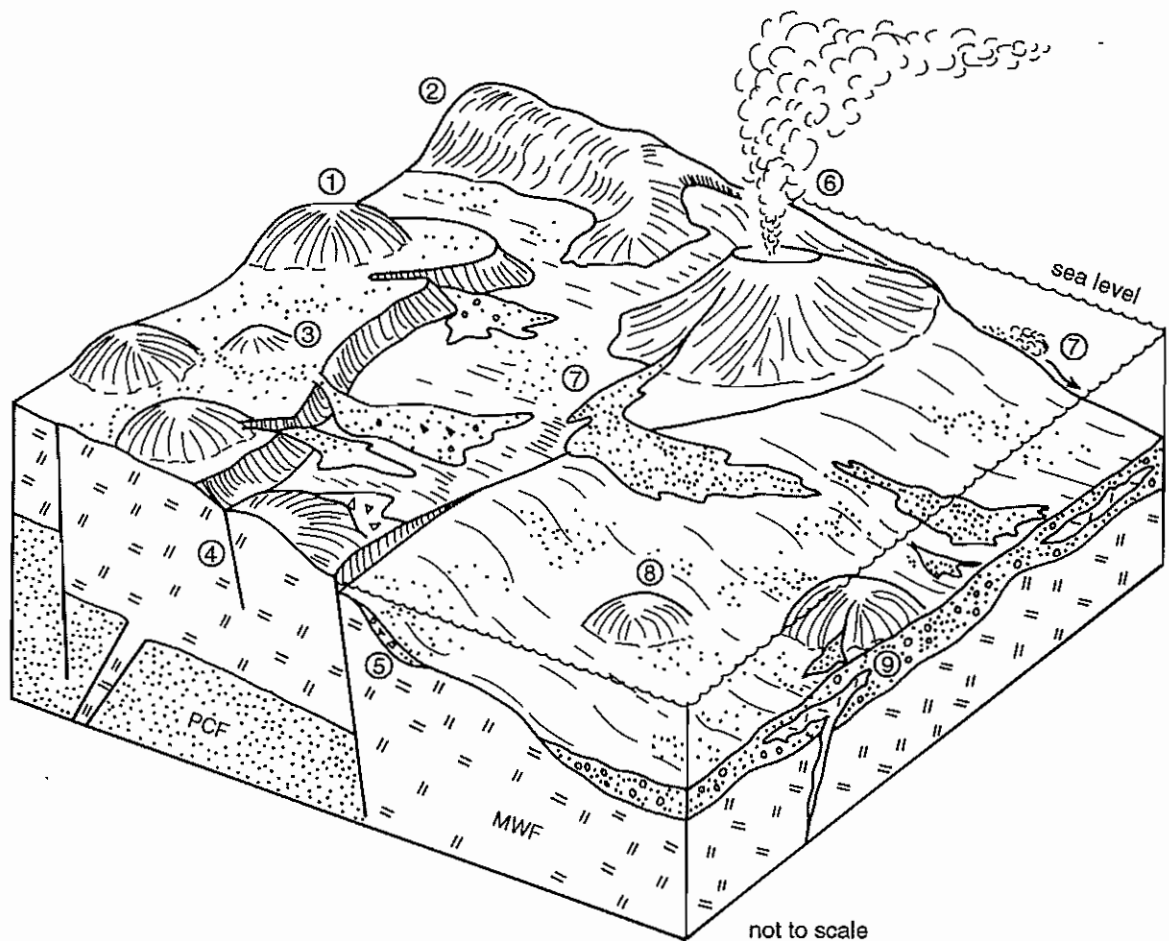


Figure 8.1 Palaeogeographic reconstruction of the Trooper Creek Formation and source terrain during deposition of the Kitchenrock Hill Member. 1 - rhyolite and dacite domes; 2 - lava; 3 - eroded domes and intrusions; 4 - syn-volcanic fault related to basin subsidence; 5 - talus adjacent to fault scarp; 6 - explosive eruptions from subaerial to shallow subaqueous volcano; 7 - syn-eruptive sediment gravity flow deposit incorporating clasts derived from Mount Windsor Formation (MWF) rhyolite and dacite; 8 - seafloor topography created by the Mount Windsor Formation domes; 9 - syn-sedimentary intrusion. PCF - Puddler Creek Formation.

Volcaniclastic facies in the Kitchenrock Hill Member also contain juvenile components. The actual sources for the juvenile components have not been identified, are not exposed or have been eroded away. However, the high proportion of pumice, shards, crystals and crystal fragments within the volcaniclastic units implies that the sediment gravity flows were sourced from explosive magmatic or phreatomagmatic eruptions, and also suggests that the volcanic centres were shallow marine or subaerial (e.g. McBirney, 1963; Chapter 3). The crystal composition (feldspar±quartz) suggests a dacitic to rhyolitic provenance. Thickness variations within the Kitchenrock Hill Member reflect palaeotopography on the depositional surface that was generated by the underlying Mount Windsor Formation lavas and/or growth faults.

Highway Member

The Highway Member comprises compositionally and texturally diverse syn-eruptive volcaniclastic facies, syn-sedimentary intrusions and lavas which are intercalated with volcanic and non-volcanic sedimentary facies. Rounded clasts of Mount Windsor Formation provenance are absent in the Highway Member. This suggests that either: (1) the source areas for clasts of Mount Windsor Formation rhyolite and dacite were completely eroded prior to deposition of the Highway Member; or (2) that basin subsidence and/or volcanic accumulation caused a change from a mixed volcanic source (i.e. Kitchenrock Hill Member) to syn-eruptive sedimentation during deposition of the Highway Member (Trooper Creek Formation).

Syn-eruptive resedimented volcaniclastic facies in the Highway Member also provide a record of the character and setting of the volcanic activity in the source areas. The source areas probably included both intrabasinal and extrabasinal volcanic centres (Fig. 8.2; Chapters 3-5). The pumiceous and crystal-rich facies contain pyroclasts that originated from magmatic and/or phreatomagmatic eruptions at extrabasinal, basin margin or shallow subaqueous intrabasinal volcanic centres. The crystal assemblage (feldspar±quartz) suggests a dacitic to rhyolitic magma composition for these facies. However, the actual source areas for the sediment gravity flows have not been identified. Intercalated siltstone and sandstone turbidites are dominated by volcanic detritus (principally shards, crystal fragments, devitrified ash) but may contain non-volcanic components (phyllite, meta-chert, tourmaline, white mica) from basement sources similar to those of the Puddler Creek Formation and Rollston Range Formation. This implies that deposition of non-volcanic detritus was the ambient sedimentation style and was interrupted during accumulation of the Mount Windsor Formation and Trooper Creek Formation.

The high proportion of scoria and bombs in the andesitic breccia facies association (Highway Member) suggests that pyroclasts were sourced from intrabasinal strombolian eruptions (Chapter 4). These eruptions built ephemeral scoria cones subject to collapse

and resedimentation, delivering scoria and bombs into deeper water flanking environments. The bomb-rich breccia facies accumulated in close proximity to source vents (cf. Staudigel and Schmincke, 1984). In the western part of the study area, intercalated turbidites and siltstone imply that the vents and depositional environment were below storm wave base and in water probably less than 500 m deep (Chapter 5). The maintenance of a marine environment during volcanic aggradation implies that basin subsidence was probably important during accumulation of the Trooper Creek Formation.

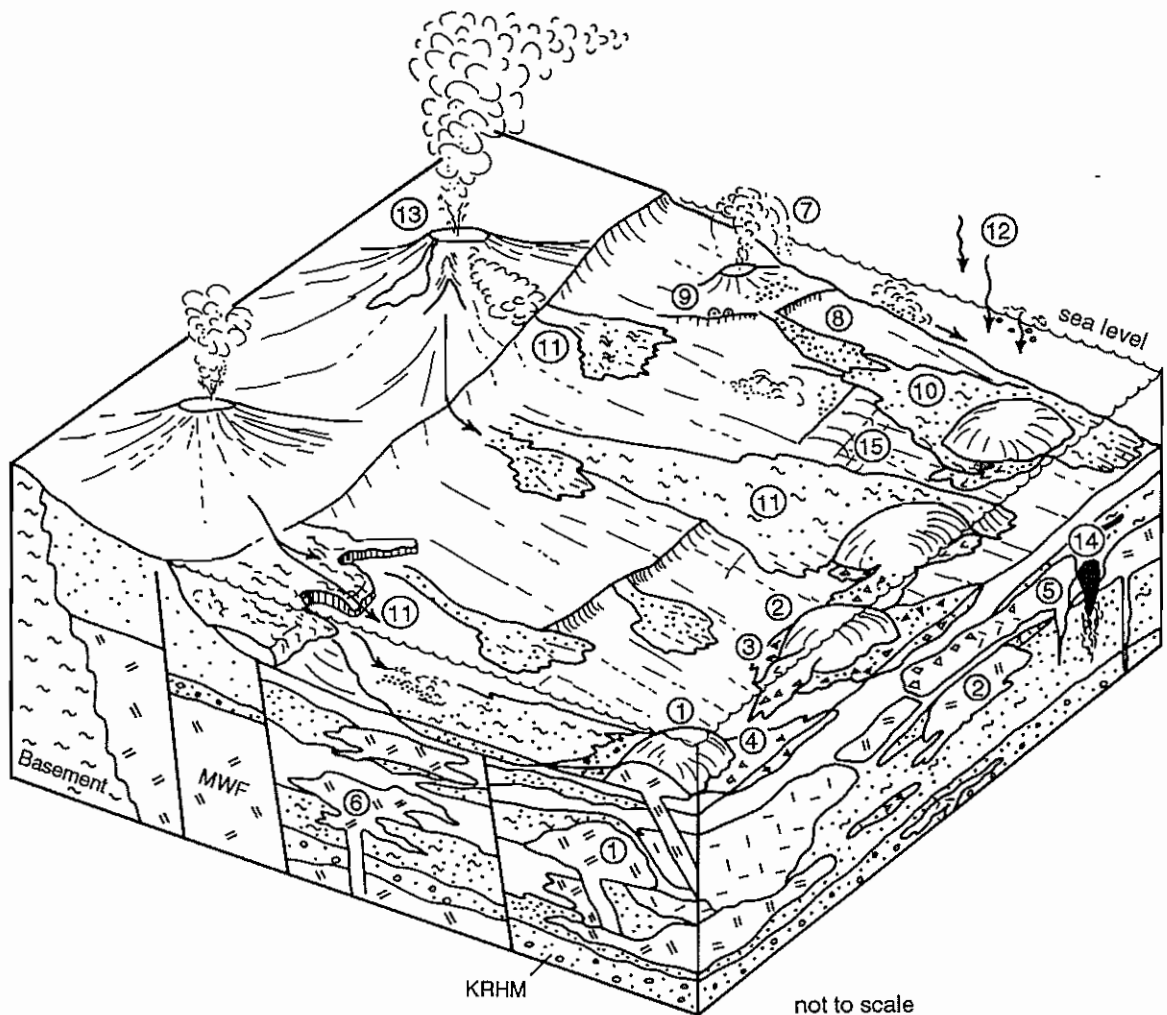


Figure 8.2 Palaeogeographic reconstruction of the Trooper Creek Formation and subaerial source area during deposition of the Highway Member at the time of mineralisation. 1 - dome; 2 - partly extrusive cryptodome; 3 - resedimented intrusive hydroclastic breccia; 4 - resedimented hyaloclastite; 5 - lava; 6 - syn-sedimentary intrusion; 7 - submarine scoria cone; 8 - resedimented andesitic scoria breccia; 9 - microbialite; 10 - ponding of syn-eruptive sediment gravity flow deposit against lava dome; 11 - syn-eruptive resedimentation of pyroclastic debris by subaqueous mass flows; 12 - water-settled ash fall; 13 - subaerial explosive rhyolitic and dacitic volcanoes sourcing pyroclasts to the basin; 14 - massive sulfide body; 15 - syn-volcanic faults. KRHM - Kitchenrock Hill Member; MWF - Mount Windsor Formation.

To the east, around Trooper Creek prospect, the andesitic volcanism constructed an edifice which shoaled to above fairweather wave base and may have been temporarily emergent (Chapter 4). The post-eruptive history of the andesitic volcanic centre began with partial collapse of the edifice, creating a stable shallow marine surface for deposition of the overlying dacitic volcano-sedimentary facies and microbialites. Volcanic siltstone and subordinate vitric-rich sandstone that are increasingly abundant in the overlying succession (Highway Member), reflect a return to relatively quiet, probably deeper water conditions in response to compaction and/or tectonic subsidence. In the west near Highway-Reward, Highway East and Coronation homestead there is no evidence for shallowing of the depositional environment towards the top of the Highway Member. This suggests that basin subsidence was regionally uneven, although largely kept pace with volcanic aggradation in the basin.

Syn-sedimentary sills, cryptodomes, partly extrusive cryptodomes and associated in situ and resedimented autoclastic facies are an important component of the Highway Member. These form the proximal facies association from intrabasinal, intrusive and extrusive, non-explosive volcanism (Chapter 5). In the Highway-Reward to Trooper Creek area, rising magma that encountered unconsolidated, water-saturated sediment commonly remained sub-surface and was emplaced as syn-sedimentary sills and cryptodomes rather than erupting as lavas and domes. The intrusions probably significantly modified the physical environment and pore fluid properties in these parts of the basin (cf. Einsele et al., 1980; Delaney, 1982; Duffield et al., 1986; Hanson, 1991; McPhie, 1993; Davis and Becker, 1994; Brooks, 1995). Dewatering, induration, disruption of bedding and low grade metamorphism commonly accompanied intrusion. The lavas, cryptodomes and sills influenced seafloor topography and therefore sedimentation, causing lateral facies and thickness variations (cf. Yamamoto et al., 1991; Davis and Villinger, 1992). The Highway-Reward VHMS deposit formed in the proximal facies association of one small, syn-sedimentary intrusion-dominated volcanic centre. At Highway-Reward, pyrite-chalcopyrite pipes and associated marginal sphalerite-galena-barite mineralisation are syn-volcanic replacements of the host sediment, syn-volcanic intrusions, cryptodomes and volcanoclastic deposits (Chapter 7). Syn-volcanic faults may have acted as conduits for ascending hydrothermal fluids and also influenced the position of the intrusion-dominated complex (cf. Berry et al., 1992; Huston, 1992).

In the study area, quartz-hematite pods and lenses ("ironstones") occur throughout Trooper Creek Formation (Chapter 6). Type 1 ironstones are characterised by positive Eu anomalies, anomalous Zn, Pb, Ag and Au, and are geochemically similar to ironstones which mark the ore equivalent of the Thalanga VHMS deposit (45 km to the west). These units are exposed at Handcuff prospect and are clear targets for further exploration. Type 2 ironstones are characterised by negative Eu and Ce anomalies, are regionally distributed

and are not associated with mineralisation. Type 2 ironstones are interpreted to have deposited from short-lived, low temperature, local hydrothermal systems in the proximal facies associations of intrusion- and lava-dominated volcanic centres and shallow marine volcanoes in the Highway Member (cf. Einsele et al., 1980; Einsele, 1986; Boulter, 1993a). Circulating fluids leached iron, silica and other elements from the glassy volcanic rocks and reprecipitated the iron and silica in the enclosing volcanic succession in response to conductive cooling and mixing with seawater (cf. Sigurdsson, 1977).

8.2.4 Rollston Range Formation

The top of the Highway Member corresponds to the end of intrabasinal volcanism and volcanic-dominated sedimentation. This was then followed by a phase of post-eruptive erosion and reworking that probably affected both basin margin and intrabasinal centres, accompanied by rare effusive and explosive eruptions, leading to deposition of the Rollston Range Formation. The lithofacies characteristics and fossils in the Rollston Range Formation imply a submarine depositional environment, below storm wave base (cf. Henderson, 1986; Chapter 3). The siltstone and sandstone units are dominated by volcanic quartz and feldspar suggesting a largely felsic volcanic source. The remaining fragment population is clearly non-volcanic (phyllite, polycrystalline quartz, detrital mica, tourmaline) and implies input from granitic and deformed basement sources. Feldspar grains are relatively unaltered and angular suggesting only minor transport and reworking. The other components are variably rounded indicating reworking in a high-energy environment prior to redeposition by sandy, high-concentration turbidity currents, and that the source areas were at least partly subaerial or shallow marine. In addition to the reduced volcanic input, tectonic uplift may have contributed to the change in the depositional style towards the top of the Trooper Creek Formation. This uplift might have exposed Precambrian basement, feeding significantly larger volumes of non-volcanic material into the basin during deposition of the Rollston Range Formation. Siltstone and sandstone units with similar provenance to those in the Rollston Range Formation also occur in the Trooper Creek Formation.

8.3 The Cambro-Ordovician tectonic setting of the Seventy Mile Range Group

Henderson (1986) and Stolz (1995) propose that the Seventy Mile Range Group is the fill of a back-arc basin developed on thinned Precambrian basement flanking a continental margin volcanic arc (Chapter 2). A reconstruction of the tectonic setting for the Mount Windsor Subprovince is beyond the scope of this study. However, the volcanic facies

analysis presented here provides constraints on the tectonic setting of the Trooper Creek Formation.

1. Local erosion of the Mount Windsor Formation occurred during deposition of the Kitchenrock Hill Member (Trooper Creek Formation). Erosion of the Mount Windsor Formation may record shoaling of the Mount Windsor Formation to above storm wave base in some parts of the basin and/or a period of differential uplift and subsidence prior to, or during deposition of the Kitchenrock Hill Member.
2. The palaeogeography of the Trooper Creek Formation comprises a marine setting (both above and below storm wave base), that flanked a subaerial or shallow water silicic volcanic terrain.
3. During deposition of the Trooper Creek Formation, the rapid accumulation of strata and continued subsidence to around or below storm wave base (e.g. Chapter 4) implies strong crustal extension (cf. Allen et al., 1996b). Evidence for local, temporary shoaling of the volcanic succession implies that basin subsidence was regionally heterogeneous but largely kept pace with volcanism and intrusion of magma.
4. Although palaeocurrent indicators are lacking in the Trooper Creek Formation, the shallowing of the depositional environment in the upper part of the Highway Member at Trooper Creek suggests a local westerly dipping palaeoslope in the upper part of the Trooper Creek Formation, between Coronation homestead and Trooper Creek prospect. The regional extent and significance of this shallowing-upward trend within the Trooper Creek Formation is unclear and requires further work.
5. Volcanism waned during the early Ordovician and deposition of the Rollston Range Formation occurred during post-eruptive erosion of a largely felsic volcanic source (Trooper Creek Formation ?, volcanic arc; cf. Henderson, 1986) and erosion of granitic and deformed basement sources. Uplift of the basement, possibly in response to a decrease in crustal extension, may have occurred at this time.

8.4 A modern analogue for the Trooper Creek Formation

The lithofacies, formative volcanic processes and volcano types represented in the Cambrian Mount Windsor Subprovince have analogues in modern successions. The offshore extension of the Taupo Volcanic Zone (TVZ) is proposed as an analogue of the Trooper Creek Formation and associated source terrain. However, it is important to note that the comparisons have several limitations.

(1) The interpretations presented here are based on mapping only a central segment of the Seventy Mile Range Group. Regional geological studies concentrating on identifying key facies associations as a means of reconstructing the facies architecture of the entire belt have yet to be undertaken. This approach will provide important insights into the evolution of the basin, source volcanoes and provenance.

(2) The combined effects of erosion and burial by younger deposits means that the understanding of the Trooper Creek Formation is incomplete, and biased towards the preserved submarine record. In the TVZ, the opposite is true, as few geological, geophysical or geochemical studies of the offshore extension of the TVZ have been undertaken. Neither is the subsurface stratigraphy of the TVZ well constrained for much of the TVZ.

(3) The original orientation and dimensions of the Seventy Mile Range Group depocentre are poorly constrained and complicated by faulting and folding (e.g. Henderson, 1986; Stolz, 1995). The subprovince presently extends east-west for approximately 165 km, is oriented east-west, and may be more than 12 km thick (Henderson, 1986).

The Taupo Volcanic Zone (TVZ) in the North Island of New Zealand is a region of major Pliocene to Quaternary calc-alkaline volcanism and crustal extension resulting from subduction of the oceanic Pacific Plate beneath the continental Australian Plate (Cole, 1990; Wilson et al., 1995; Fig. 8.3). The TVZ is a NNE trending zone of vent and caldera structures extending for 200 km onshore from Ohakune in the south, northward through the central North Island, and offshore for around 150 km (e.g. Wright, 1992). The boundary between the TVZ and the Kermadec Ridge-Havre Trough system (its counterpart to the NNE) is marked by a NW–SE-trending structural discontinuity which is coincident with, but separate from, the Vening Meinesz Fracture Zone (Gamble et al., 1993). The Kermadec Ridge-Havre Trough system and the TVZ are offset sinistrally by approximately 50 km (Wright, 1992; Gamble et al., 1993; Fig. 8.3). The TVZ is about 20–60 km wide, and is bounded to the east and west by faults, and dominantly Mesozoic greywacke basement. Little is known of the basement beneath the TVZ as it is buried beneath 2–3 km of volcanic units (Rogan, 1982). A total volume of 15 000–20 000 km³ of volcanic products is estimated to have erupted from the TVZ (Houghton et al., 1995). At present the TVZ is rifting at rates between 7 and 18 mm/a (Wilson et al., 1995) and subsiding at approximately 1 to 2 mm/a (Nairn and Beanland, 1989; Wright, 1992). Episodes of uplift and erosion affected the TVZ between c. 1 Ma and 0.32 Ma (Wilson et al., 1995).

The TVZ is divided into three segments (Wilson et al., 1995; Houghton et al., 1995). The northeast and southwest segments contain andesitic to dacitic composite volcanoes and lack calderas, whereas the central segment (125 km long) is dominantly rhyolitic (Wilson

et al., 1995; Houghton et al., 1995). The northeast segment extends offshore. The central TVZ includes at least eight caldera volcanoes. These account for 34 caldera-forming eruptions in the approximately 1.6 Ma history of the central TVZ (Wilson et al., 1995). Andesitic activity marking the onset of TVZ volcanism began at approximately 2 Ma. Cole (1990) divided the onshore and offshore segments of the TVZ into an eastern andesitic–dacitic continental arc, which is best developed in the northern and southern segments of the TVZ, and a marginal back arc basin characterised by bimodal basaltic–rhyolitic volcanism. However, this model is not universally accepted (e.g. Wilson et al., 1995).

Rhyolite is the dominant magma erupted in the whole TVZ (Wilson et al., 1995). Andesite is an order of magnitude less abundant, and dacite and andesite are volumetrically minor. Rhyolitic eruptions have generated ignimbrites, fall deposits and domes. The remaining compositions manifest in a variety of forms including tuff rings, scoria cones, fall deposits, lavas, domes, sills and pyroclastic flow deposits (Wilson et al., 1995).

Sedimentation in the offshore segment of the TVZ includes detritus from Upper Palaeozoic to Mesozoic rocks in the eastern part of the North Island and volcanic components from the TVZ (Lewis and Pantin, 1984). Terrigenous sedimentation is relatively continuous, whereas volcanic sedimentation is episodic and dominantly derived from onshore rhyolitic eruptions in the TVZ. Volcanic debris is delivered to the basin via rivers or directly from fallout (e.g. Lewis and Pantin, 1984) or by pyroclastic flows which reach the shoreline (e.g. Walker, 1979). The current fluvial input is minor as the onshore TVZ is being drained mainly by a river system which discharges on the west coast (e.g. Lewis and Pantin, 1984). Water-settled fallout and resedimented pyroclast-rich deposits, account for the greatest volume of sediment within the offshore TVZ (Lewis and Pantin, 1984). Volcanism within the offshore TVZ extends between the active andesitic White Island massif, northward along the Ngatoro Ridge, to the submarine Whakatane arc volcano (Gamble et al., 1993). These volcanic centres are an important syn- and post-eruptive source of basaltic, andesitic and minor rhyolitic and dacitic detritus to offshore TVZ (e.g. Lewis and Pantin, 1984). Whakatane volcano is inactive and comprises basaltic and andesitic lava flows and talus deposits (Gamble et al., 1993). The Ngatoro Ridge is studded with numerous vents, fissures and lava fields comprising sheet flows, pillows and talus fans (e.g. Wright, 1992; Gamble et al., 1993). In some areas, these deposits are blanketed by rhyolitic pumice clasts from an unknown source (Gamble et al., 1993). Submarine rhyolitic dome complexes and associated breccia facies flank White Island (Gamble et al., 1993). Andesitic detritus sourced from eruptions at White Island are largely restricted to <15 km from the volcano. However, volcanoclastic units derived from White Island occur in sediments up to 60 km from the source (Kohn and Glasby, 1978).

Shelf sediments in the offshore TVZ display varying provenance characteristics (Lewis and Pantin, 1984). Sediments in the western and central part of the shelf dominantly comprise volcanogenic sand sourced from the onshore TVZ and andesitic-dacitic eruptions from White Island. Some units contain epiclasts sourced from eroded intrabasinal rhyolitic and andesitic knolls (Lewis and Pantin, 1984; Kohn and Glasby, 1978). In the eastern part of the shelf, sediments are dominantly non-volcanic and delivered to the basin by rivers draining the adjacent greywacke ranges (Lewis and Pantin, 1984). On the shelf slope, late Pleistocene and Holocene sedimentation rates are around 0.1 to 0.2 m/ka (Kohn and Glasby, 1978). Water depths range from a few 10s of metres to > 3 km (e.g. Lewis and Pantin, 1984).

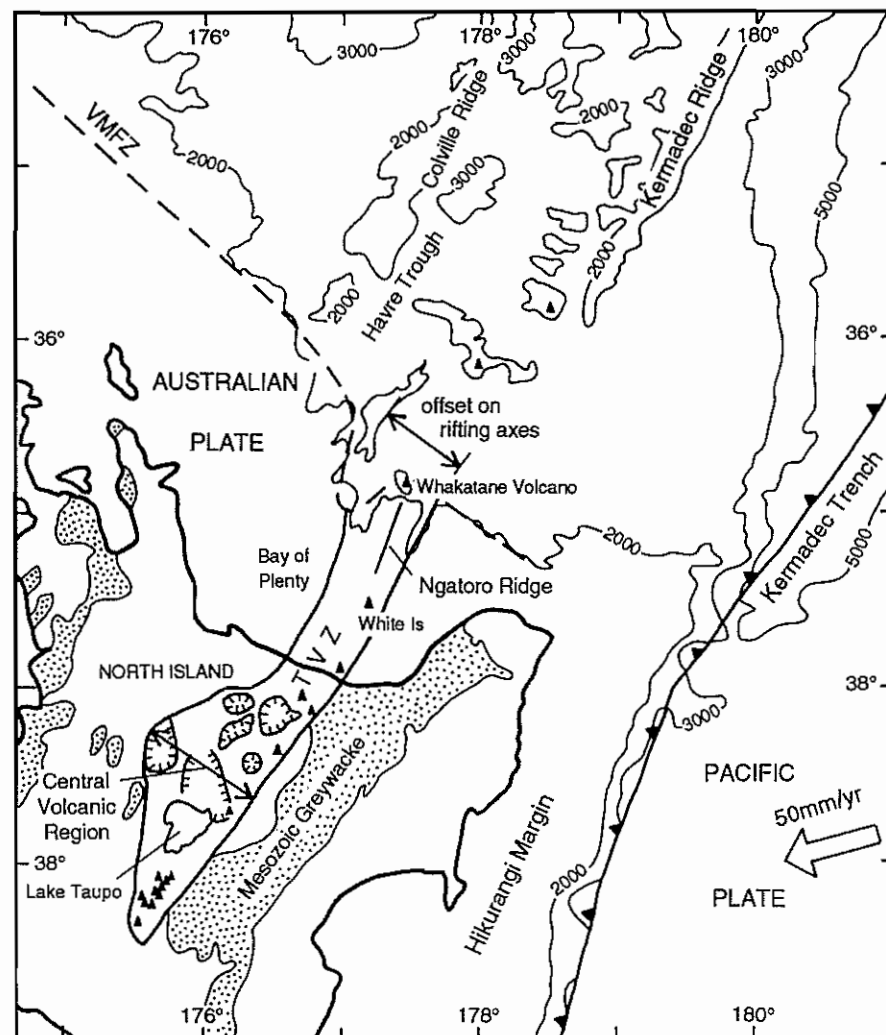


Figure 8.3 Structural setting of the Taupo Volcanic Zone (TVZ) of the North Island of New Zealand. Quaternary andesitic volcanoes are shown as solid triangles. The location of the central TVZ and position of major rhyolitic calderas is also shown. The position of the Vening Meinesz Fracture Zone (VMFZ) is from Wilson et al. (1995). Isobaths are in metres. Arrows show the direction of subduction of Pacific Plate beneath the Australian Plate. Modified from Davey et al. (1995).

The palaeogeographic setting of the Trooper Creek Formation and associated source terrain is envisaged to have been similar to that of the modern TVZ. Like the offshore TVZ, sedimentation in the Trooper Creek Formation included episodic influxes of pyroclasts from explosive eruptions at subaerial or shallow-submarine volcanic centres and from eruptions in relatively deep subaqueous environments. The style of eruptions represented by volcanoclastic facies in the Trooper Creek Formation are interpreted to have been similar to some of the volcanism in the TVZ (e.g. Gamble et al., 1993; Wilson et al., 1995). Caldera-forming explosive eruptions in the source terrain may have been an important source of pyroclasts that were finally deposited in submarine environments. However, there is no positive evidence such as caldera-collapse megabreccias, very thickly ponded pumiceous mass-flow deposits or caldera-margin growth faults (e.g. Busby-Spera, 1986) to indicate that caldera volcanoes were present within the study area.

The interleaving and juxtaposition of volcanic facies observed in the Trooper Creek Formation is presently taking place in the offshore TVZ (e.g. Lewis and Pantin, 1984). Basin subsidence, syn-volcanic faulting and episodes of uplift are important elements of the TVZ and are likewise recorded in the Trooper Creek Formation.

However, the TVZ differs from the Trooper Creek Formation in several ways. (1) Although the dimensions of the Trooper Creek Formation depocentre are poorly constrained the regional extent of the preserved succession (160 km) is significantly less than the dimensions of the TVZ; (2) In the Trooper Creek Formation, intrabasinal volcanoes contributed a greater volume of volcanic detritus to the depocentre than basin margin or subaerial volcanic centres. In contrast, the onshore extension of the TVZ is the focus of current magmatism, and is more extensive than the offshore segment; (3) Unlike the TVZ, the supply of terrigenous sediment to the Trooper Creek Formation depocentre was limited and overwhelmed by volcanic sedimentation; and (4) The Trooper Creek Formation contains several major VHMS deposits. Massive sulfide mineralisation has not been recorded in the offshore TVZ.

8.5 Implications for comparable volcanic successions

The research undertaken here has relevance to understanding comparable ancient submarine volcanic successions and assessing prospective host sequences for massive sulfide mineralisation.

(1) Studies of silicic submarine volcanoes are largely limited to ancient volcanic successions, such as the Seventy Mile Range Group, that are now exposed on land. The

present study has contributed to the understanding of volcanic facies generated by felsic to intermediate eruptions in submarine environments. In particular, the importance of syn-sedimentary intrusions in submarine volcanic successions, and the lithofacies associations which characterise intrusion- and lava-dominated volcanic centres are documented (Chapter 5). The research constrains models for the growth of silicic lavas and intrusions, and suggests that they can play an important role in influencing the pore fluid properties of the volcanic succession and the location, geometry and chemistry of syn-volcanic submarine hydrothermal systems (Chapters 6-7).

(2) Although major advances have been made in understanding the chemistry and evolution of Australian VHMS deposits, few studies have evaluated the interrelationships between volcanism and mineralisation. Detailed definition of the lithofacies and palaeovolcanologic setting of the Seventy Mile Range Group in the area around the Highway-Reward deposit has allowed for recognition of those parts of the volcanic succession that are most prospective for VHMS deposits (Chapter 3). The results of the research can be applied to other parts of the Seventy Mile Range Group and comparable submarine volcanic successions elsewhere.

(3) The literature on VHMS deposits emphasises mineral deposition within caldera settings. This analysis suggests that silicic, syn-sedimentary intrusion-dominated submarine volcanic centres are also important settings for some massive sulfide deposits. The present study also highlights the importance of sub-seafloor replacement during massive sulfide accumulation. Based on a study of the Highway-Reward deposit and the few other published descriptions of sub-seafloor deposits, the various circumstances by which sub-seafloor deposits can develop have been summarised and the implications for mineral exploration assessed (Chapter 7).

(4) In the study area, type 1 ironstones have geochemical signatures which suggest they may be associated with as yet undiscovered massive sulfide mineralisation (cf. Duhig et al., 1992; Davidson, 1996), whereas type 2 ironstones are interpreted as deposits from hydrothermal fluids circulating around lavas, intrusions and explosive volcanic centres (Chapter 6). Ironstones occur within the host successions to many Australian VHMS deposits. In these successions, type 2 ironstones may also be targets for exploration.

8.6 Avenues for further research

A comprehensive analysis of the Seventy Mile Range Group concentrating on recognition of distinctive facies and facies associations with the aim of reconstructing the Cambro-Ordovician facies architecture has yet to be completed. The research presented here

suggests that this approach will provide important insights into lithofacies, composition, depositional environment and volcanic history of the Seventy Mile Range Group. The proposed study will also allow for recognition of other parts of the Seventy Mile Range Group that are prospective for as yet undiscovered VHMS deposits. There are several important topics which should be addressed. These include: (1) a determination of the regional extent of the Kitchenrock Hill Member in the Trooper Creek Formation (Chapter 3); (2) an evaluation of the regional significance of a shallowing upward trend in the Highway Member (Trooper Creek Formation) at Trooper Creek prospect (Chapter 4); (3) further assessment of the potential for some key facies associations within the Trooper Creek Formation to be traceable over several tens of kilometres (Chapter 3); and (4) clarification of the lithofacies comprising the Rollston Range Formation (Chapter 3).

The Mount Windsor Formation comprises a thick sequence of rhyolitic and dacitic lavas, domes, intrusions, subordinate volcanoclastic rocks and rare sedimentary units (e.g. Berry et al., 1992; Chapter 3). The formation extends for over 60 km within the Mount Windsor Subprovince. Extensive silicic submarine lava- and intrusion-dominated volcanic successions have been little studied (e.g. Gibson, cited in Cas, 1992), in part due to their relative scarcity in modern environments. The quality of outcrop available in large parts of the Mount Windsor Formation will allow precise volcanic facies definition, an interpretation of the style of volcanic activity and evaluation of the depositional setting. The research could be undertaken during systematic geological mapping of the Seventy Mile Range Group.

There are few detailed descriptions of sub-seafloor replacement style VHMS deposits. In particular, the geochemistry of hanging wall alteration associated with sub-seafloor replacement deposits remains poorly understood. Detailed definition of the lithofacies and volcanic history of the host succession to the Highway-Reward deposit provides a framework for geochemical studies of alteration associated with a sub-seafloor replacement style Cu-Au-rich VHMS deposit. Detailed mineralogical, paragenetic, fluid inclusion and isotope studies of the massive sulfide orebodies could form part of this research. The results of the proposed research will have applications for mineral exploration in the Seventy Mile Range Group and other ancient volcanic successions.

8.7 Summary

A detailed analysis of the Mount Windsor Formation and Trooper Creek Formation in the area between Coronation homestead and Trooper Creek prospect has led to a better understanding of the stratigraphy and palaeovolcanology of the central part of the Mount Windsor Subprovince. The preserved lithofacies were deposited in a submarine

environment. The first stage of Trooper Creek Formation volcanism and sedimentation (Kitchenrock Hill Member) reflects local post-eruptive erosion of the Mount Windsor Formation rhyolitic and dacitic units, and contemporaneous subaqueous (syn-eruptive) redeposition of rhyodacitic to dacitic, pyroclastic debris generated at an adjacent subaerial or shallow marine, explosive volcanic terrain. Minor siltstone units, turbidites, lavas and intrusions were also emplaced in the basin (below storm wave base) during this stage. The overlying Highway Member comprises compositionally and texturally diverse volcanoclastic facies which are intercalated with volcanic and non-volcanic sedimentary facies. The volcanoclastic facies reflect resedimentation of pyroclastic and autoclastic detritus, sourced intrabasinally (andesitic–rhyolitic volcanic centres) and from an adjacent subaerial or shallow marine, rhyolitic to dacitic, explosive volcanic terrain. The top of the Highway Member marks the end of volcanic-dominated sedimentation. This was then followed by a phase of post-eruptive erosion and reworking of volcanic deposits in the source terrain with rare eruptions of lava and incursions of rhyodacitic sediment gravity flows, leading to deposition of the Rollston Range Formation. The Rollston Range Formation includes significant basement-derived detritus and was deposited in a marine environment (below storm wave base).

The palaeogeographic setting, lithofacies and formative volcanic processes represented by the Trooper Creek Formation are similar to those documented (e.g. Gamble et al., 1993; Wilson et al., 1995) in TVZ, New Zealand.